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APPLICATION NUMBER: ***60/554,865***
FILING DATE: ***March 19, 2004***
RELATED PCT APPLICATION NUMBER: ***PCT/US05/09478***

UNITED STATES PATENT AND TRADEMARK OFFICE · DEPARTMENT OF COMMERCE

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PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c).

Express Mail Label No. EL919128927US

INVENTOR(S)		
Given Name (first and middle [if any])	Family Name or Surname	Residence (City and either State or Foreign Country)
Nigamananda	Samal	Tempe, Arizona

Additional inventors are being named on the 1 *separately numbered sheets attached hereto*

TITLE OF THE INVENTION (500 characters max)

SINGLE MODE HIGH POWER VCSELs

Direct all correspondence to: **CORRESPONDENCE ADDRESS**

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ENCLOSED APPLICATION PARTS ***(check all that apply)***

☑ Specification *Number of Pages* 8

☑ Drawing(s) *Number of Sheets* 11

☐ Application Data Sheet. See 37 CFR 1.76

☐ CD(s), Number

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☑ Applicant claims small entity status. See 37 CFR 1.27.

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Respectfully submitted,

SIGNATURE [signature]

TYPED or PRINTED NAME Thomas D. MacBlain

TELEPHONE 602-530-8088

Date 3/19/04

REGISTRATION NO. 24,583
(if appropriate)
Docket Number: 9138-0146

USE ONLY FOR FILING A PROVISIONAL APPLICATION FOR PATENT

PROVISIONAL APPLICATION COVER SHEET
Additional Page

Docket Number	9138-0146

INVENTOR(S)/APPLICANT(S)

Given Name (first and middle [if any])	Family or Surname	Residence (City and either State or Foreign Country)
Shane	Johnson	Chandler, Arizona
Yong-Hang	Zhang	.Scottsdale, Arizona

Number 1 of 1

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[X] Applicant claims small entity status. See 37 CFR 1.27

TOTAL AMOUNT OF PAYMENT	($) 80.00

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Application Number	
Filing Date	herewith
First Named Inventor	Samal et al!
Examiner Name	
Art Unit	
Attorney Docket No.	9138-0146

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1001	770	2001	385	Utility filing fee	
1002	340	2002	170	Design filing fee	
1003	530	2003	265	Plant filing fee	
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1005	160	2005	80	Provisional filing fee	80

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2. EXTRA CLAIM FEES FOR UTILITY AND REISSUE

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Independent Claims		- 3** =		X		=	
Multiple Dependent						=	

Large Entity Fee Code	Large Entity Fee ($)	Small Entity Fee Code	Small Entity Fee ($)	Fee Description
1202	18	2202	9	Claims in excess of 20
1201	86	2201	43	Independent claims in excess of 3
1203	290	2203	145	Multiple dependent claim, if not paid
1204	86	2204	43	** Reissue independent claims over original patent
1205	18	2205	9	** Reissue claims in excess of 20 and over original patent

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1052	50	2052	25	Surcharge - late provisional filing fee or cover sheet	
1053	130	1053	130	Non-English specification	
1812	2,520	1812	2,520	For filing a request for *ex parte* reexamination	
1804	920*	1804	920*	Requesting publication of SIR prior to Examiner action	
1805	1,840*	1805	1,840*	Requesting publication of SIR after Examiner action	
1251	110	2251	55	Extension for reply within first month	
1252	420	2252	210	Extension for reply within second month	
1253	950	2253	475	Extension for reply within third month	
1254	1,480	2254	740	Extension for reply within fourth month	
1255	2,010	2255	1,005	Extension for reply within fifth month	
1401	330	2401	165	Notice of Appeal	
1402	330	2402	165	Filing a brief in support of an appeal	
1403	290	2403	145	Request for oral hearing	
1451	1,510	1451	1,510	Petition to institute a public use proceeding	
1452	110	2452	55	Petition to revive - unavoidable	
1453	1,330	2453	665	Petition to revive - unintentional	
1501	1,330	2501	665	Utility issue fee (or reissue)	
1502	480	2502	240	Design issue fee	
1503	640	2503	320	Plant issue fee	
1460	130	1460	130	Petitions to the Commissioner	
1807	50	1807	50	Processing fee under 37 CFR 1.17(q)	
1806	180	1806	180	Submission of Information Disclosure Stmt	
8021	40	8021	40	Recording each patent assignment per property (times number of properties)	
1809	770	2809	385	Filing a submission after final rejection (37 CFR 1.129(a))	
1810	770	2810	385	For each additional invention to be examined (37 CFR 1.129(b))	
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SUBMITTED BY				(Complete *(if applicable)*)	
Name *(Print/Type)*	Thomas D. MacBlain	Registration No. (Attorney/Agent)	24,583	Telephone	602-530-8088
Signature	[signature]			Date	3/19/04

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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicant: Samal et al.

Filed: Herewith

Title: **SINGLE MODE HIGH POWER VCSELs**

CERTIFICATE OF MAILING BY EXPRESS MAIL
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1. Provisional Application for Patent Cover Sheet (1 page);
2. Fee Transmittal for FY 2004 (1 page in duplicate);
3. Specification (8 pages plus cover sheet);
4. Drawings (11 sheets);
5. Check for $80.00; and
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3/19/2004
Date

Suzanne Shields
Suzanne Shields

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Express Mail Label No. EL919128927US

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Provisional Patent Application

Title: **SINGLE MODEL HIGH POWER VCSELs**

Inventor(s): **Nigamananda Samal, Tempe, Arizona**
Shane Johnson, Chandler, Arizona
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SINGLE MODE HIGH POWER VCSELs

This invention relates to a new structural design in optoelectronic semiconductor laser to enhance the single mode power.

Background

Single mode high power VCSELs

VCSELs or Vertical Cavity Surface Emitting Laser, is a semiconductor micro-laser diode that emits light in a cylindrical beam, vertically from the surface of a fabricated wafer, and offers significant advantages when compared to the edge-emitting lasers currently used in the majority of fiber optical communications systems. When compared with edge-emitters, VCSEL's offer lower threshold currents, low-divergence circular output beams, higher direct modulation speed, longitudinal single mode emission, ease of integration to form 2-D arrays and higher coupling efficiency into optical fiber. However, high fiber-coupling efficiencies are only reached at low optical powers, because with increasing output power, higher order transverse modes are supported by the cavity. In general, the complex transverse modal behavior of VCSELs at high pump rates is a major drawback for many practical applications. The modal behavior, just like most of the other key properties of the VCSELs, depends strongly on the confinement mechanism. Despite many of their inherent advantages over its rivals, VCSELs still suffer from many inadequacies. most prominent are "limited power" and lack of "modal purity." These unresolved issues have compelled the VCSEL to enjoy only 10% share of the whole semiconductor laser market.

Typical VCSEL applications include optical data links, proximity sensors, encoders, laser range finders, laser printing, bar code scanning and last but surely not the least, optical storage.

Different effects in the cavity influencing the modal behavior of the laser

Multi mode behavior due to inhomogeneous spatial gain distribution:

The distinction between the influences of different effects such as pump induced current spreading, spatial hole burning and thermal gradients inside the cavity on the carrier distribution have been discussed by Degen et al. [1] These complex and partly counteracting effects tend to produce high order transverse modes in the optical cavity. The pump-induced inhomogeneities predominantly govern the carrier distribution in the laser [1]. These inhomogeneities arise

purely from the current flow through the confinement area and not from an interaction with optical fields in the cavity. This conclusion is supported by the results of theoretical simulations by Nakwaska [2]. His modeling results in distributions of the current density inside the carrier confinement region show distinct maxima at the borders of the VCSEL and a deep dip in the center. Our modeling results also show the same behavior as shown in Fig. 1. These distributions are in good agreement with the experimental results of Degen et al. [1] and they favor strongly towards the emission of high order modes, which is due to inhomogeneous spatial gain distribution.

Multi mode behavior due to spatial hole burning:

The tendency to high order mode emission is further enhanced by spatial hole burning, which is due to interaction between optical field and the carrier reservoir in the cavity. The influence of these effects on the carrier distribution and on the lasing near-field have been modeled in detail by Zhao et al. [3] and by Nakwaska et al. [4]. The influence of spatial hole burning is much smaller than the effect of current spreading, but it further enhances the tendency to higher order mode emission [3] [4].

Multi mode behavior due to strong thermal gradients inside the cavity:

A third effect that forces the laser to high order mode emission is the presence of strong thermal gradients in the cavity. These gradients have also been modeled by Nakwaski et al. [4] and temperature differences larger than 30K have been predicted between the center and the border region of the VCSEL. These differences originate from Joule-heating and heating by non-radiating recombination processes. Thus, the temperature differences will be highest for injection currents larger than the thermal rollover point, because the injection current is already high and non-radiating recombination is on the rise. As a consequence of this thermal gradient, carriers will be thermally excited and redistributed towards higher energies. This effect of spectral carrier redistribution is stronger in the hot center of the VCSEL and weaker at the cooler periphery. The strong redistribution of carriers in the center of the VCSEL obviously leads to a broad dip in the carrier distribution and eventually to multi-mode spectrum.

The above effects have been well explained and experimentally demonstrated by several authors [1], [3], [4]. The effect of inhomogeneous carrier distribution is seen as the most predominant mechanism towards governing the modal behavior in the cavity. There are some more second order effects like diffusion of carriers in the active region and carrier

recombination. The influence of these effects could be assumed minimal in comparison to the effect due to inhomogeneous pump profile or carrier distribution.

Prior Art:

A few related patents are cited below.

1. Jiang et al., U.S. patent No. 6,021,146 issued February 1, 2001. This approach uses the idea of heavy doping in the central region of the laser beam path to facilitate current confinement in the center, eventually to suppress overcrowding at the edge of the aperture.

2. Jiang et al., U.S. patent No. 6,026,111 issued February 15, 2000. This approach to realize single mode operation relies on the idea of using an extended cavity which introduces high modal loss to high order laser modes while supporting the lower order modes.

3. Gopinath, U.S. patent No. 6,515,305 B2 issued February 4, 2003. This approach uses the idea of photonic band gap crystal fabrication on the top of the VCSEL, which promotes mode confinement by index guiding.

Approach 1. involves a risk of degrading the active layer and increasing free carrier absorption. So the power output is limited. Approach 2. suffers from low speed of the device, as the cavity length is very long. Approach 3. involves complex processing steps, which adds to the cost.

Summary

A novel approach is proposed here to control modal behavior in the cavity of VCSEL both at higher injection and higher temperature. This is realized by profiling the spatial current distribution and a robust thermal management scheme. Spatial current distribution is engineered by suitably positioning multiple current apertures of different size. Finally the processing includes a robust thermal management scheme such as deep electroplated via hole on the back or substrate removal and bonding to metal to bring down the junction temperature.

This invention relies on engineering the spatial distribution of the injection current profile by using multiple oxide apertures of varying size and varying distance from the active layer. Simpler device design and growth, simpler device processing, better yield, lower cost and better performance of the laser are provided.

In comparison to the prior art discussed above, our idea of using multiple apertures with varying size offers a very robust technique for single mode high power VCSELs. It does not add

any complexity to either growth or processing. The different size of the apertures could be realized by several ways, i.e. self-aligned mesa process, simple intracavity device processing or growing different concentrations of Al mole fraction in the oxide layers.

Advantageous and novel here are:

1. The use of multiple apertures of varying size either by lateral oxidation technique or ion implantation or a combination thereof in VCSEL or edge emitting devices to suppress transverse modes.

2. The use of multiple apertures at optimized locations in the device so as to tailor the shape of the spatial distribution of the carriers in the active region.

3. The use of multiple apertures along with some on-wafer heat management schemes namely, a) electroplated via hole, or b) epitaxial lift off to produce high power in the device.

These inventive features can be used in many optoelectronic devices, which have a multi-billion dollar market, to name a few, VCSEL, FP edge emitting laser, DFB and DBR lasers.

References:

[1] C. Degen, W. Elsaber and I. Fischer, "Transverse modes in oxide confined VCSELs: Influence of pump profile, spatial hole burning, and thermal effects," Opt. Express 5, 38 - 47 (1999), http://www.opticsexpress.org/abstract.cfm?URI=OPEX-5-3-38.

[2] W. Nakwaski, "Current spreading and series resistance of proton-implanted vertical-cavity top-surface-emitting lasers," Appl. Phys. A 61, 123 - 127 (1995).

[3] Y. G. Zhao and J. McInerny, "Transverse-Mode Control of Vertical-Cavity Surface-Emitting Lasers," IEEE J. Quantum Electron. 32, 1950 - 1958 (1996).

[4] W. Nakwaski and R. P. Sarzala, "Transverse modes in gain-guided vertical-cavity surface-emitting lasers," Opt. Commun. 148, 63 - 69 (1998).

Brief Description of the Drawings

Fig. 1 is a diagrammatic cross-sectional illustration of a VCSEL of the present invention;

Fig. 2 is a plot of current density, Jy (A/cm^2) vs. distance from center for a conventional VCSEL;

Fig. 3 is a series of plots of current density Jy (A/cm^2) at different locations between two apertures vs. distance from center for a VCSEL according to the present invention;

Fig. 4 is a plot of current density Jy (A/cm^2) vs. distance from center and showing contour of current for the VCSEL of the invention;

Fig. 5 is a series of plots of current density Jy (A/cm^2) distribution vs. distance from center for a large VCSEL in accordance with the invention;

Fig. 6 is a diagrammatic cross-sectional illustration of VCSEL of the invention and shows the layers and features of the device;

Fig. 7 contains plots of light current voltage (LIV) characteristics for a VCSEL according to the invention;

Fig. 8 (a) and 8 (b) are photographs of a VCSEL in accordance with the invention before (a) and after (b) gold electroplating;

Fig. 9 contains plots of LIV characteristics of a VCSEL in accordance with the invention before and after electroplating;

Fig. 10 plots LIV characteristics of a VCSEL in accordance with the invention in which a p-aperture is at 7^{th} mirror pair in p-DBR and n-aperture at 1^{st} mirror pair in n-DBR; and

Fig. 11 is a series of plots of spectra of a VCSEL like that of Fig. 10 at differing current injections.

Detailed Description

Single mode control for high power VCSELs

The schematic diagram of the invention is shown in Fig. 1. At least two oxide apertures with different sizes are located on each side of the active region with varying distance from the active region. The current confinement and spreading in the cavity is controlled by the size and position of the oxide apertures. It is shown by our theoretical modeling that the current distribution strongly favors of single mode operation if the size and distance of the apertures from the active region are optimally chosen.

A few novel features of the mode controlled VCSEL are:

- Multiple oxide apertures to provide controlled spatial carrier distribution.
- Relative placement of the apertures to optimize the spatial carrier distribution.
- Relative size of the apertures to optimize the spatial carrier distribution.
- Tailoring the doping profile of the DBR mirror with multiple oxide apertures to optimize the carrier distribution for large size devices.

The idea uses a minimum of two oxide apertures with different size and locations to tailor the current injection profile to match the fundamental mode of the optical field distribution profile. Gain is a logarithmic function of the injection current spatial distribution J(y). A bell-shape or near-Gaussian shaped spatial current distribution is a good candidate to help sustain only fundamental transverse mode in the cavity. It is clearly predicted that using two optimally placed apertures in the device the spatial distribution of the current can be tailored to offset the detrimental effect of spatial hole burning. In the model we have neglected the second order effects like diffusion, carrier recombination and existing optical field in the cavity.

Detailed 3D modeling was carried out using Femlab, a popular finite element tool, to see the effect of double oxide-aperture to profile the spatial carrier distribution. Fig. 2 shows the theoretical modeling results for a conventional VCSEL design, where the oxide layer is at the first null of the E-field in the p-mirror, which is placed roughly one mirror pair away from center of the cavity. In the conventional VCSEL design people tend to place the oxide layer as close as the first null of the E-field to favor index guiding by the oxide layer and enhance current confinement in the active area. At smaller aperture and smaller injection, optical wave guiding effect becomes dominant thereby supporting single mode. From Fig. 2 it is clearly seen that the current distribution is not in favor of single mode operation despite the help of index-guiding effect because the carrier distribution has distinct maximas on the periphery of the aperture area. Therefore, this conventional structure design can only support single mode operation at smaller aperture, at around ~ 5μm, resulting in a very small output power, 1-2mW.

Fig. 3 shows one of the many optical designs of VCSEL modeled by us, which uses two oxide apertures placed relatively on suitable positions so that carriers are funneled and spread in a controlled manner so as to induce a near-Gaussian shape of spatial current density. In this particular design, the p-mirror oxide aperture is six mirror pairs away from the cavity center and has a diameter of 5 um and the n-mirror aperture is two mirror pair away from the cavity center and has a diameter of 15 um. Fig. 4 shows surface current density and contour line in this design. This optimum position and size is also a function of doping density in the epi-layers in the DBR. In the original of Fig. 4 the color scale to the right of the figure ranges from deep blue at the bottom to green to yellow (at D) through orange to deep red (at A and above). A copy of the original, in color is supplied for the Patent and Trademark Office file for this provisional.

The approximate coloration of the current density diagram to the left of the figure are indicated by the letters A - D which are also indicated on the color scale.

A few of the things observed from the modeling results are:

1. For each set of relative size of oxide apertures (which decides the active-device size) there is an optimum relative position, which gives near Gaussian shaped spatial current density.

2. For each relative position of the oxide layers there is an optimum set of relative sizes of the apertures.

3. By varying the doping the shape of the optimum spatial current distribution can be fine-tuned.

So a design rule based on the model results can be formulated.

In Fig. 5 an optimum design has been modeled for fairly a large size device. The device size is around 17 microns. The current density shows a near-Gaussian profile. The "at cavity centre" curve shows the spatial current distribution in the active region. The p-oxide is 13 mirror pair away and n-oxide is one mirror pair away.

Avenues of future investigation could be in using more than two apertures in the device and alterations in the doping profile.

The above-mentioned idea of mode control could be employed also in edge emitting Fabry Perot, DFB and DBR lasers.

To address the thermal effect on the VCSEL, several schemes have been proposed here. One way for VCSELs on-wafer thermal management, as shown in Fig. 6, is to etch a deep via through the substrate and electroplate the back and front sides of the wafer with thick gold to disperse the heat and eventually bring down the junction temperature. Another way is to lift off the epitaxial layers of the device and bond it onto a heat sink substrate either metal or ceramic.

Experimental Results

Several 1050nm VCSEL wafers were grown in Arizona State University using MBE. Test results are shown here.

Fig. 7 shows LIV characteristics of a double aperture VCSEL with 17-micron p-aperture and 27-micron n-aperture. The peak power is more than 20 mW @ 33 mA. The peak wall plug efficiency is more than 30%. The threshold current is measured to be less than 2mA and threshold voltage looks to be slightly above 1 volt. Fig. 8 shows pictures of a fabricated VCSEL

before and after electroplating. After around 6 micron thick gold electroplating there is an enhancement of peak power by nearly 15% as shown in Fig. 9. This VCSEL design has the p-aperture at 3rd mirror pair in the p-mirror and n-aperture is on the first mirror pair in the n-mirror. As the p-aperture is not at the optimized position it shows an oxide peak in the spectrum as a result the VCSEL is not single mode. However, by moving the p-aperture farther away from the active region the spectral purity gets better as shown in Fig. 11.

While a preferred, exemplary embodiment of the invention has been described above, modifications and changes may be made as will be apparent to those skilled in the art without departure from the spirit and scope of the invention as set forth in the appended claims and claims to be added to a complete utility patent application.

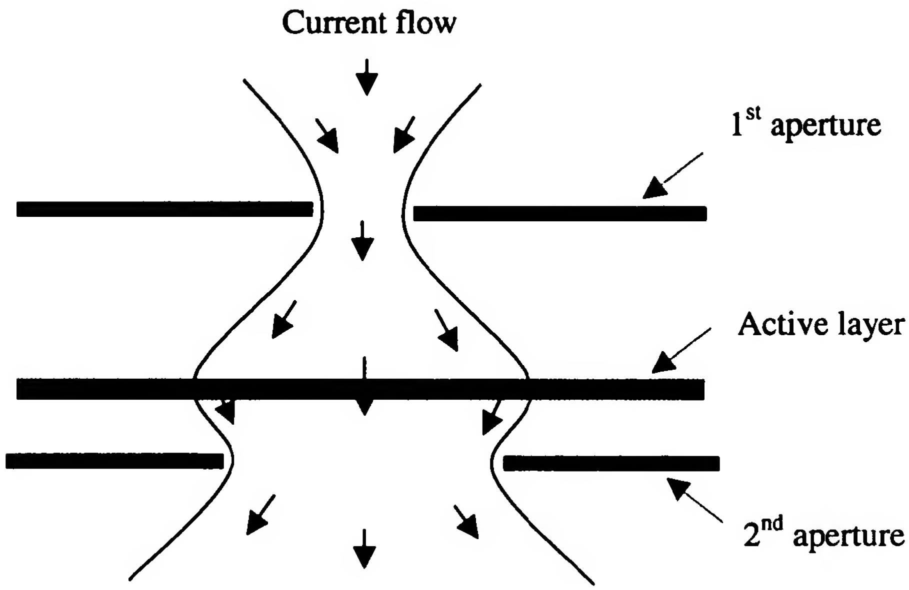

Fig. 1: Schematic diagram of the proposed idea of a novel VCSEL design.

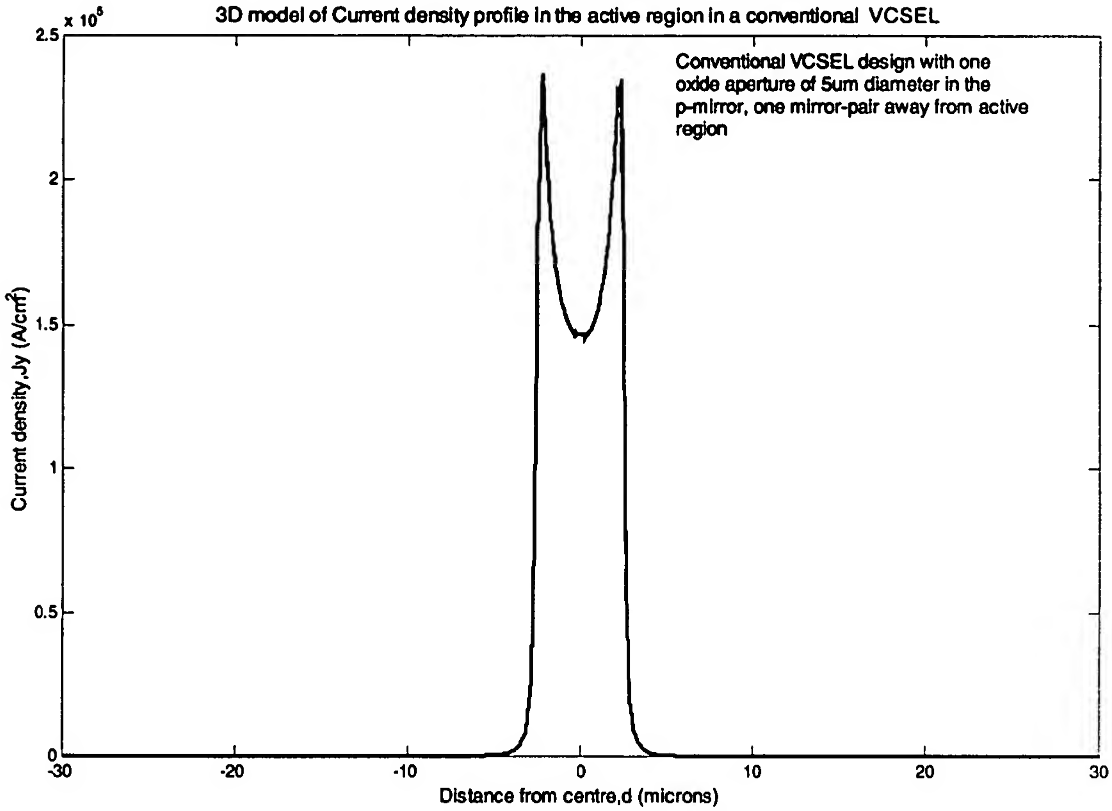

Fig. 2: Theoretical modeling results of current density distribution for a conventional VCSEL design.

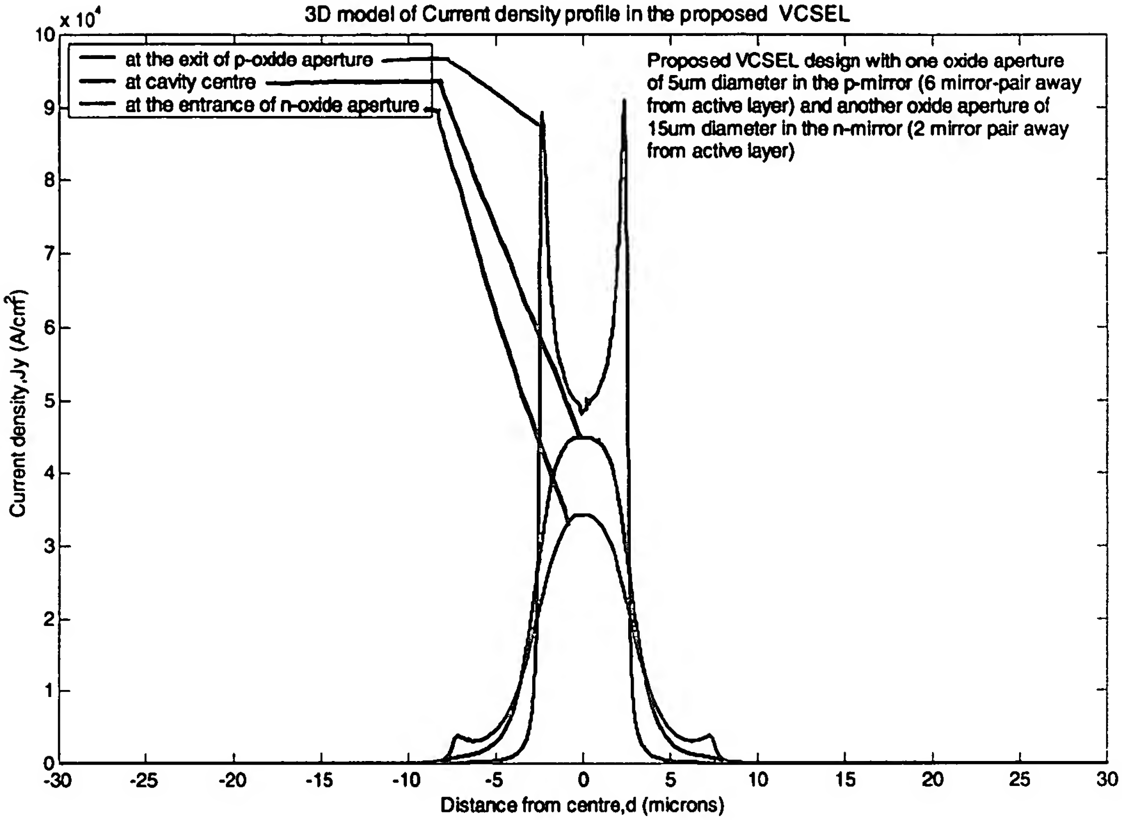

Fig. 3: Theoretical modeling results of current density distribution for an optimum VCSEL design. The black line gives the current density distribution in the active region while the other curves give the current density distribution at other locations between two apertures in the p- and n-DBR, respectively.

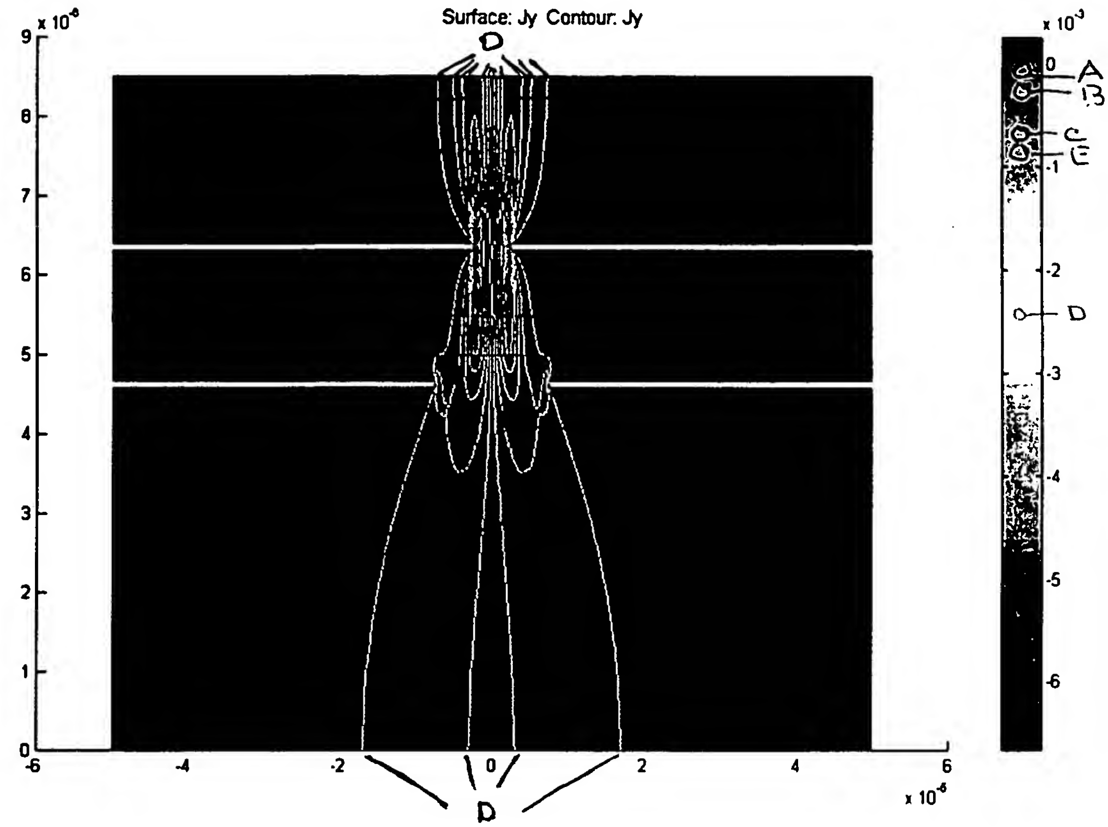

Fig. 4. surface current density and contour of current across the proposed VCSEL.

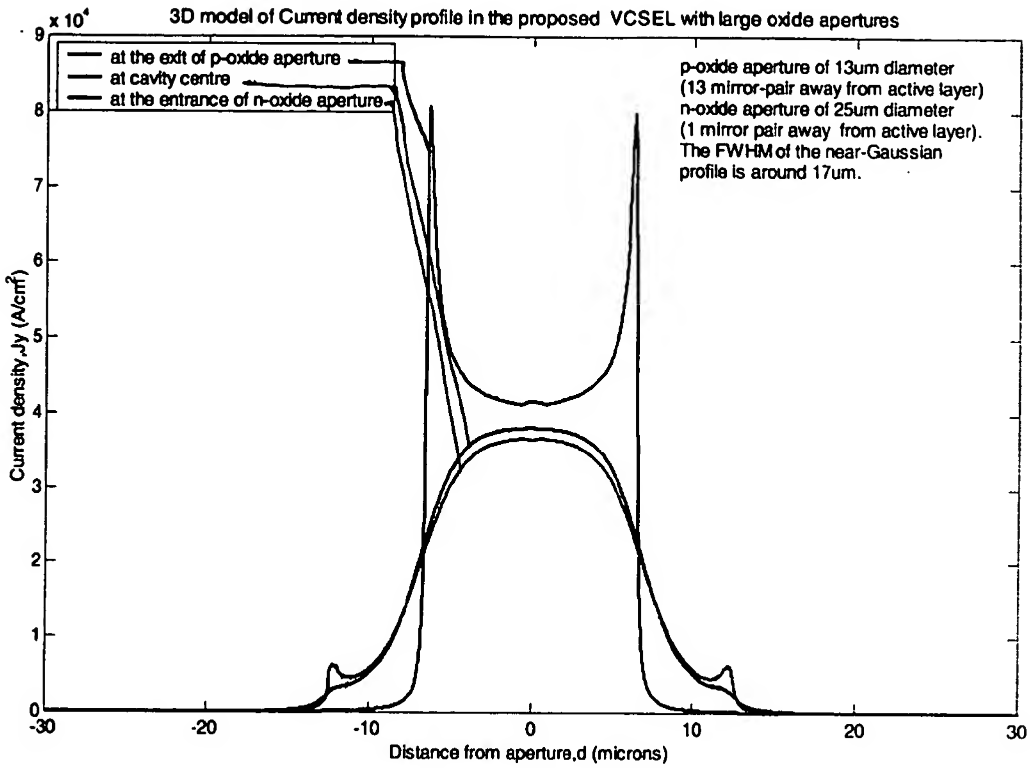

Fig. 5: Theoretical modeling results of current density distribution for a large size VCSEL design. The black line gives the current density distribution in the active region while the other curves give the current density distribution at other locations between two apertures in the p- and n-DBR, respectively.

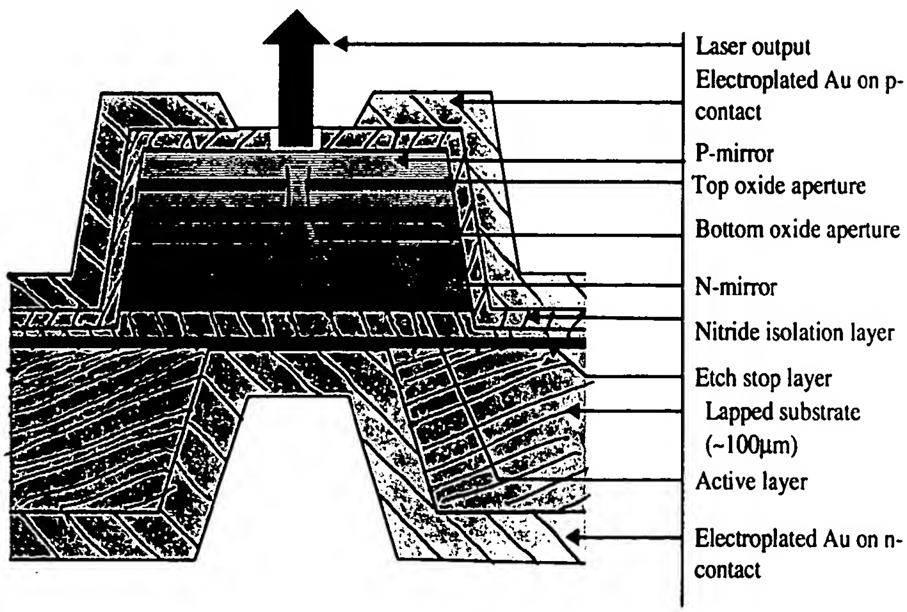

Fig. 6 Schematic diagram of the proposed VCSEL design that includes one of the thermal management schemes and the optimized single mode control

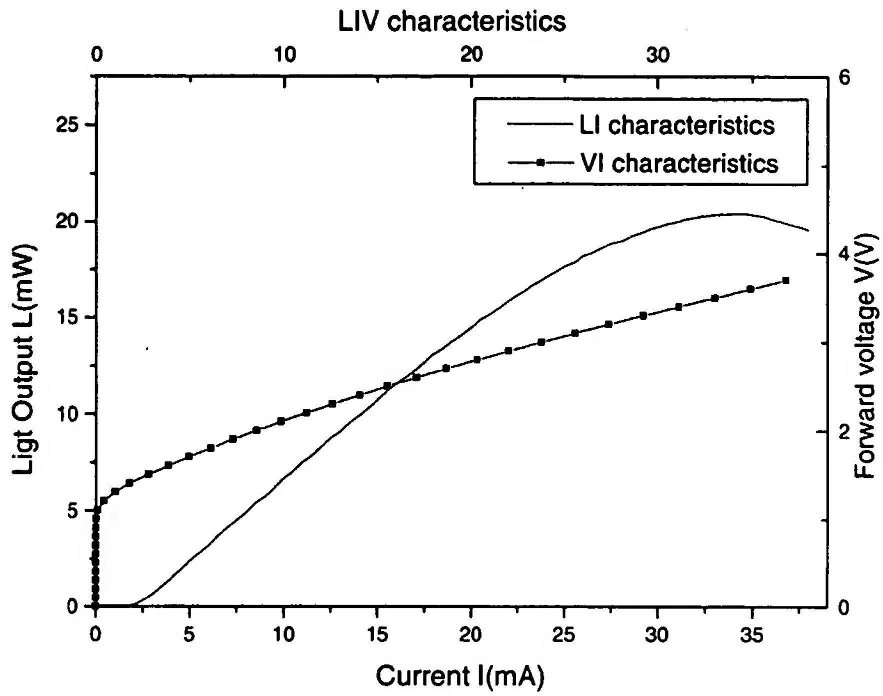

Fig. 7 LIV characteristics of a 1050nm VCSEL with p-aperture of 17micron and n-aperture of 27 microns

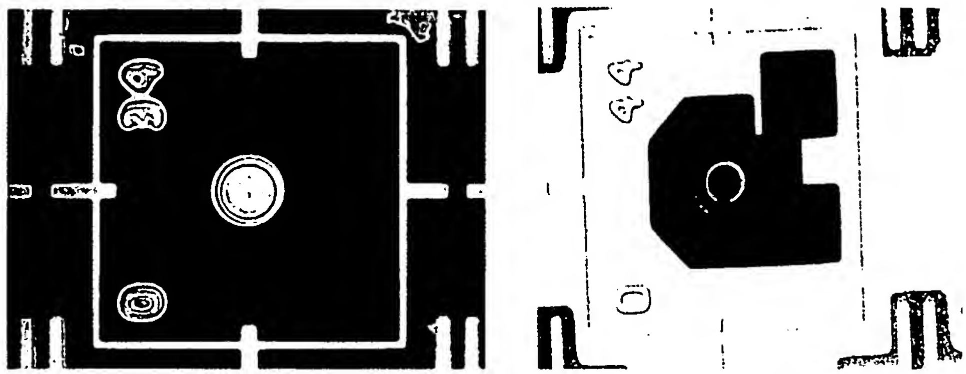
(a) (b)

Fig.8 (a) picture of a VCSEL before gold electroplating (b) picture of a VCSEL after gold electroplating

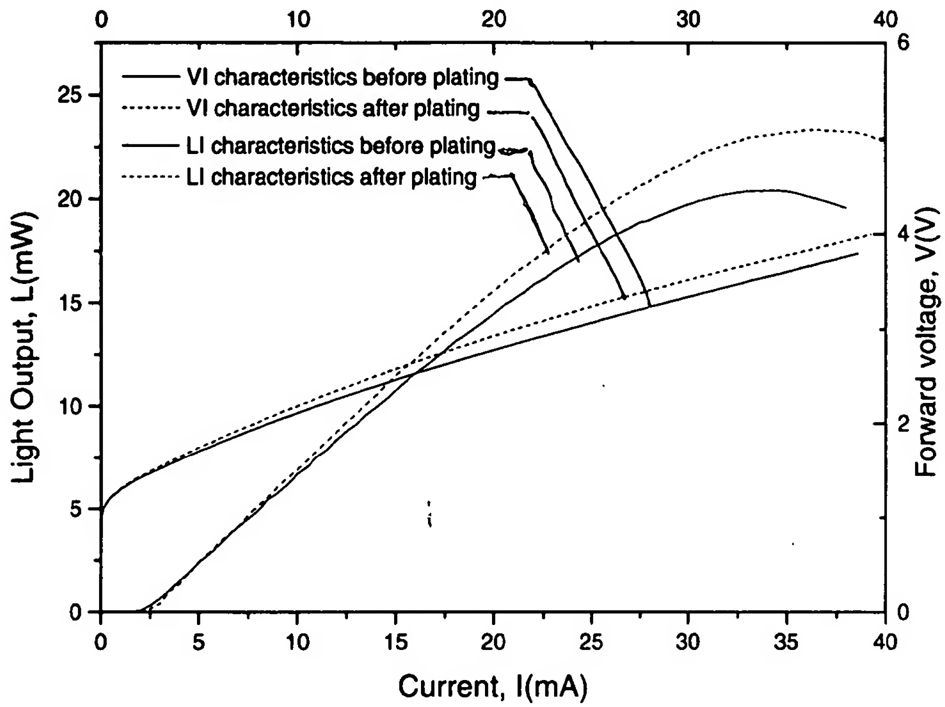

Fig.9 LIV characteristics of double aperture VCSEL before and after electroplating on top

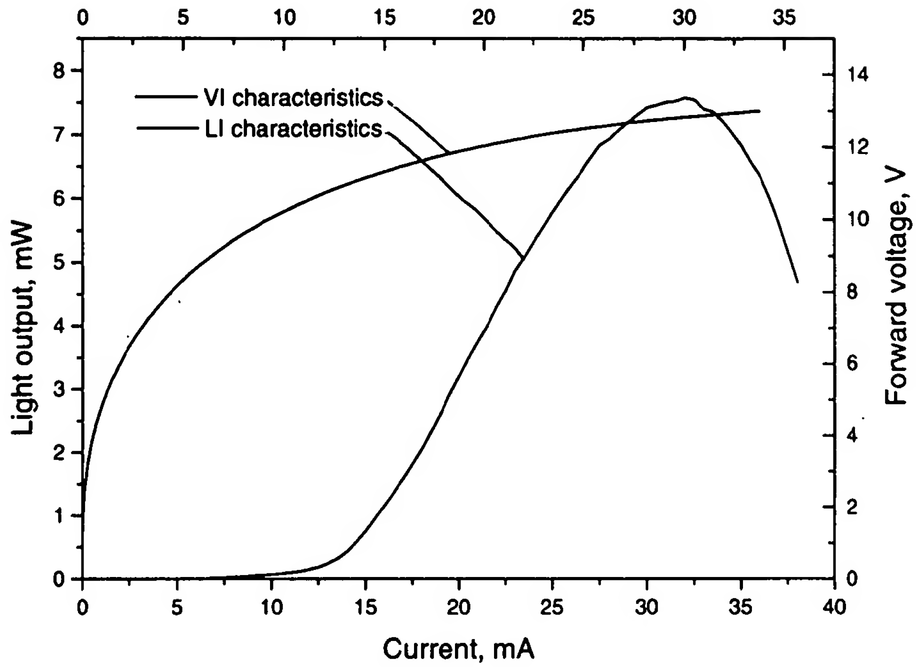

Fig. 10 LIV characteristics of a double aperture VCSEL whose p-aperture is at 7th mirror pair in p-DBR and n-aperture at 1st mirror pair in n-DBR

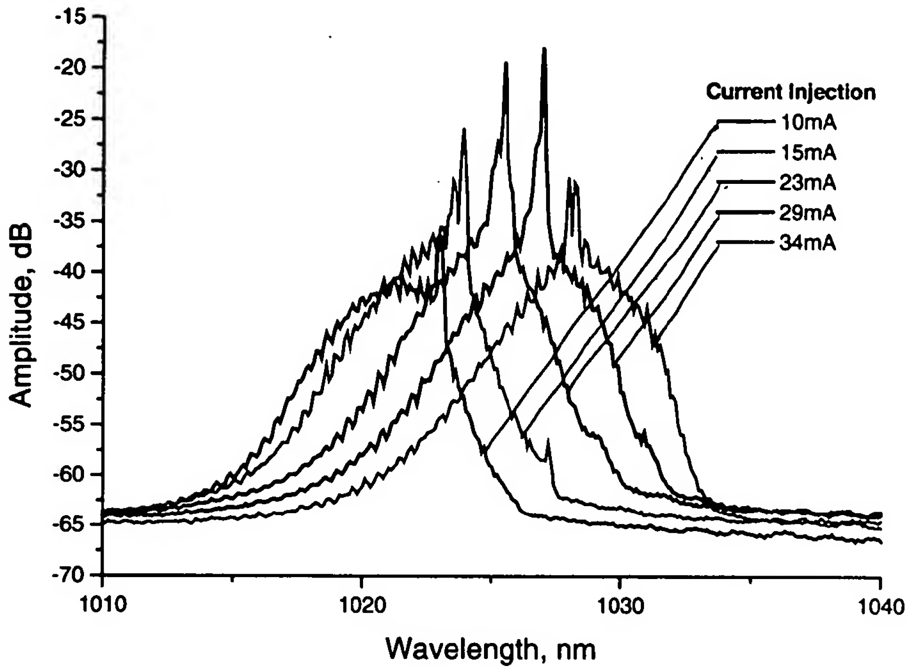

Fig. 11 Spectrum of a double aperture VCSEL whose p-aperture is at 7th mirror pair in p-DBR and n-aperture at 1st mirror pair in n-DBR